Cyclic Current Rating of Single-Core XLPE Cables with Respect to Designed Life Time

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Abstract – **This paper deals with cyclic current rating of single-core XLPE cable buried in the ground. Cyclic current rating obtained by IEC60853-1 and IEC60853-2 standards is conservative because it is based on the assumption that maximum temperature during the cycle is equal to maximum allowed steady-state temperature. Using the Arrhenius-IPM electrothermal life model, cyclic rating factor of single-core XLPE cables is calculated for assigned design life of cables.**

Keywords – **Single-core cables, Cyclic current rating, Electrothermal life model.**

I. INTRODUCTION

The rated current of HVAC cables involves operation at the rated temperature, i.e. the maximum allowed continuous temperature of cable insulation, and cables are designed under the conservative constraints that their maximum temperature is steady and equal to rated temperature. The methods for calculation of overload capacity of cables under cyclic loading are given in [1-6]. Overload capacity is quantified by cyclic rating factor. Standard IEC60853-1 gives method for calculating the cyclic rating factor for cables where internal thermal capacitance can be neglected. Simplified method in this standard requires only knowledge of shape of the load variation for not more than six hours immediately preceding the time of maximum temperature and an average value for times before that. The method can be applied to all sizes and types of cable for nominal voltage up to and including 18/30 (36) kV. Standard IEC60853-2 gives manual method for calculating cyclic rating factor for cables whose internal thermal capacitance cannot be neglected. In general, this method is applied to cables for voltages greater then 18/30 (36) kV. Cyclic ratings include temporary overloads under condition that rated temperature is not exceeded.

In this paper overload capability of single-core XLPE cables buried in the ground is analyzed. Firstly the temperature of cable is calculated for typical daily cycle diagram of HVAC cables. Using the Arrhenius-IPM electrothermal life model, expected life time of single-core XLPE cables is calculated for different values of overload factor, as well as failure rate at the end of design life time.

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II. THERMAL RESPONSE OF CABLE AND CYCLIC RATING FACTOR

Loading of HVAC power cables varies on the daily cycles. In order to perform computations for variable loading, a daily load curve is divided into a series of steps of constant magnitude and the same duration as that illustrated in Fig. 1. Duration of one step is Δt_i=24/N, where N is the number of steps. For different successive steps, the computations are done repeatedly, and the final result is obtained using the principle of superposition. The variation of the cable conductor temperature during a stepwise-constant load cycle can be determined by calculating the thermal response of the HVAC cable and the surrounding environment to each step change of load current. The two partial temperature transients are solved separately in sequence and then combined, thereby finding an analytical solution for the whole transient as follows.

Transient temperature rise of the conductor above the ambient, due to the i^{th} step of stepwise-constant load cycle is:

$$\theta_i(t) = \theta_{c,i}(t) + \alpha_i(t)\theta_{e,i}(t) \quad (1)$$

where $\theta_{c,i}(t)$ is transient temperature rise of the conductor above cable surface, $\theta_{e,i}(t)$ is cable surface temperature rise above ambient and $\alpha_i(t)$ is attainment factor. Transient temperature rise of the conductor above cable surface is calculated as:

$$\theta_{c,i}(t) = W_{J,i}[T_a(1-e^{-at}) + T_b(1-e^{-bt})] \ , \quad (2)$$

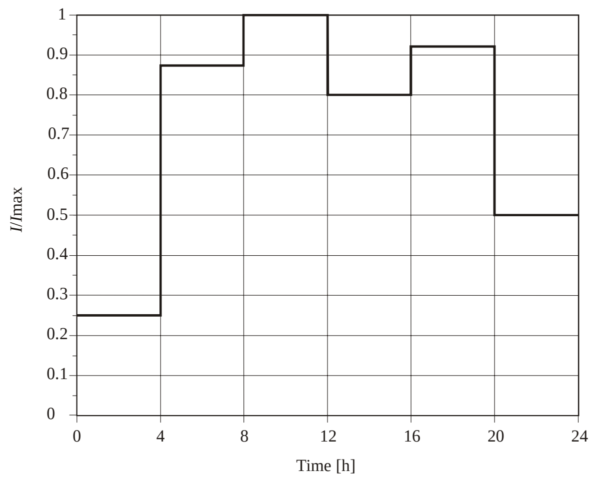

Fig. 1. Daily load cycle

where $W_{J,i}$ is power loss per unit length in a conductor due to the i^{th} current step, and T_a, T_b, a, b are thermal resistances and corresponding coefficients of the first loop of CIGRE transient two-loop network [6].

For the case of three single-core cables buried directly in the ground in a flat formation temperature rise of cable surface above the ambient is:

$$\theta_e(t) = \frac{\rho_{tz} W_{1,i}}{4\pi}\left\{-\mathrm{Ei}\left(-\frac{D_c^2}{16 t\delta}\right) + \mathrm{Ei}\left(-\frac{L^2}{t\delta}\right) + 2\left[-\mathrm{Ei}\left(-\frac{d_1^2}{16 t\delta}\right) + \mathrm{Ei}\left(-\frac{d_1'^2}{t\delta}\right)\right]\right\}, \quad (3)$$

where ρ_{tz} is thermal resistivity of soil, δ is diffusivity, D_c is outer diameter of cable, d_1 is center-to-center distance between cables, $d_1' = \sqrt{(2L)^2 + d_1^2}$, $W_{1,i} = W_{J,i}(1+\lambda_1)$, λ_1 is sheath loss factor, and Ei is exponential integral [9].

The attainment factor in equation (1) is calculated as:

$$\alpha_i(t) = \frac{\theta_{c,i}(t)}{W_{J,i}(T_a + T_b)} . \quad (4)$$

Finally, temperature of conductor is obtained adding the temperature rise for each step of the load diagram, calculated by (1), to temperature of the ground and temperature rise due to dielectric losses. Electrical resistance of conductor and corresponding joule losses are calculated with respect to temperature of conductor reached in each step of daily diagram.

The cyclic rating factor is the factor by which rated current may be multiplied to obtain the permissible peak value of current during a daily cycle such that the conductor attains, but does not exceed rated temperature. For calculating cyclic rated factor, according to standard IEC60853-2, only load cycle over a period of six hours before the time of maximum temperature is needed, while earlier values are replaced with constant one, proportional to loss-load factor. Therefore, the cyclic rating factor is given by:

$$M = \frac{1}{\left(\sum_{i=0}^{5} Y_i \left(\frac{\theta_R(i+1)}{\theta_R(\infty)} - \frac{\theta_R(i)}{\theta_R(\infty)}\right) + \mu\left(1 - \frac{\theta_R(6)}{\theta_R(\infty)}\right)\right)^{1/2}} \quad (5)$$

where:

$$\frac{\theta_R(t)}{\theta_R(\infty)} = \alpha(t)(1 - k_1 + \beta(t) k_1) \quad (6)$$

$$k_1 = \frac{W_1(T_4 + \Delta T_4)}{W_J(T_A + T_B) + W_1(T_4 + \Delta T_4)} \quad (7)$$

$$\beta(t) = \frac{\rho_{tz}}{4\pi(T_4 + \Delta T_4)}\left\{-\mathrm{Ei}\left(-\frac{D_c^2}{16 t\delta}\right) + \mathrm{Ei}\left(-\frac{L^2}{t\delta}\right) + 2\left[-\mathrm{Ei}\left(-\frac{d_1^2}{16 t\delta}\right) + \mathrm{Ei}\left(-\frac{d_1'^2}{t\delta}\right)\right]\right\} . \quad (7)$$

Thermal resistance T_4 for cable buried directly in the ground is:

$$T_4 = \frac{\rho_{tz}}{2\pi}\ln\left(\frac{2L}{D_c} + \sqrt{\left(\frac{2L}{D_c}\right)^2 - 1}\right), \quad (8)$$

while thermal resistance ΔT_4 in the case cable line consisted of three single-core cables is:

$$\Delta T_4 = \frac{\rho_{tz}}{\pi}\ln\left(\frac{d_1'}{d_1}\right) . \quad (9)$$

Obviously, the method for cyclic rating factor calculation does not respect variation of conductor temperature and assumes that joule losses are directly proportional to square of current. The results obtained on this way are therefore also conservative.

III. ELECTROTHERMAL LIFE MODEL

Electrical stress and thermal stress are dominant aging factors for HVAC cables. The most popular electrothermal life model is the combination of two popular single-stress life models, the Arrhenius model for thermal life and the Inverse power model for electrical life [7,8]. Expected life time of the cable whose temperature is T and electric field in insulation is E can be calculated:

$$L = L_0\, e^{-B\,cT}\left(\frac{E}{E_0}\right)^{-(n_0 - b\,cT)} , \quad (10)$$

where E_0 is value of electric field below which electrical aging is negligible, cT=1/T_0-1/T is conventional thermal stress, T_0 is reference temperature, n_0 is voltage endurance coefficient, L_0 is life at T=T_0 and E=E_0, B=$\Delta W/k$, ΔW is activation energy of the main thermal degradation reaction, k is Boltzmann constant, and b is parameter that rules synergism between electrical and thermal stress. The parameters of Arrhenius-IPM model for XLPE insulation are given in Table I. During one step of daily stepwise-constant load cycle temperature of insulation varies. Therefore, different values of thermal life of cable insulation are obtained for each moment during the day. Loss-of-life fraction relevant to the i^{th} step of stepwise-constant load diagram (Fig.1) is defined as:

$$LF_i = \int_0^{\Delta t_i} \frac{dt}{L_i(T)} . \quad (11)$$

TABLE I
PARAMETERS OF ARRHENIUS-IPM MODEL

Parameter	Value
b [K]	4420
B [K]	12430
n_0 [non-dimensional]	15
E_0 [kV/mm]	5
T_0 [K]	293
β_t	2

According to Miner's cumulative damage theory, the sum of all loss-of-life fractions should yield 1 at failure. So, number of cycles to failure (number of days to failure in case of daily cycles) is:

$$K = \left(\sum_{i=1}^{N} LF_i \right)^{-1} . \qquad (12)$$

Design life of cable corresponds to certain design failure probability. The cumulative probability distribution function that is commonly used for associating time to failure probability in case of polymeric insulation for power cables is the Weibull's one. Failure probability at mission time t_p is:

$$P(t_p, E, T) = 1 - e^{[-(t_p / L_{63\%})^{\beta_t}]} . \qquad (13)$$

where β_t is share parameter of cumulative probability distribution function and $L_{63\%}$ is failure-time with 63.2% probability. The relevant failure rate at time t_p can be estimated through the following hazard function:

$$h(t_p, E, T) = \frac{\beta_t}{L_{63\%}} \left(\frac{t_p}{L_{63\%}} \right)^{\beta_t - 1} . \qquad (14)$$

Based on the equation (14) failure rate can be calculated for insulation of cable loaded by defined daily stepwise-constant cycle at the end of design life time.

IV. TEST EXAMPLE

The procedure described in the previous sections is applied to HVAC XLPE insulated single-core cables [10] with aluminum conductors and copper wire screen. Maximum voltage of cables is 123 kV. The data about cables are shown in the Table II. In Table II S_c is conductor cross section, d_c is diameter of conductor, D_i is diameter above the insulation, δ_i is insulation thickness, D_c is outer diameter of cable, and I_r is rated current for considered cable formation and used bonding method of metal screens. It is assumed that three single-core cables laid in a flat formation and metal screen of cables are cross-bounded.

Laying depth of cables is 1 m, ground temperature 20°C and distance between cables is $d_1 = D_k + 70$ mm. Design life of cables is 30 years, while rated temperature of conductor is 90°C. Thermal resistivity and thermal capacity of cross-linked polyethylene is 3.5 Km/W and $2.4 \cdot 10^6$ J/(m^{3}K), thermal resistivity of soil 1 Km/W, and thermal capacities of aluminum and copper are $2.5 \cdot 10^6$ J/(m^{3}K) and $3.45 \cdot 10^6$ J/(m^{3}K) respectively. An assumption of constant electric field equal to design values is used. Currents that correspond to each step of daily load cycle are given in Table III.

Daily variation of conductor temperature for single-core XLPE cable with 1000 mm^2 cross-section is shown in Fig. 2 for different values of overload factor (maximum current relative to rated current). For overload factor value of 1.1 difference between maximum and minimum temperatures is only 17ºC (varies between 48ºC and 65ºC), while for overload factor value of 1.4 this difference is 41ºC. For overload factor value of 1.2, the maximum temperature of conductor is close to 90ºC. The last row of Table II shows the results of cyclic rating factor calculated by (5). As can be seen, these values vary in very narrow range between 1.173 and 1.185. For 1000mm^2 cross-section cyclic rating factor has value of 1.176.

TABLE II
CABLE DATA

S_c [mm^2]	630	800	1000	1200	1400
d_c [mm]	29.8	33.7	37.9	42.8	46.4
D_i [mm]	58.6	62.5	67.3	73.8	77.4
δ_i [mm]	13	13	13	13	13
D_c [mm]	72.3	76.8	82	89.5	93.3
I_r [A]	740	845	950	1025	1100
M	1.173	1.176	1.176	1.182	1.185

TABLE III
DAILY LOAD CYCLE

Step. No.	Time [h]	I/I_{max}
1	00-04	0.25
2	04-08	0.875
3	08-12	1
4	12-16	0.8
5	16-20	0.917
6	20-24	0.5

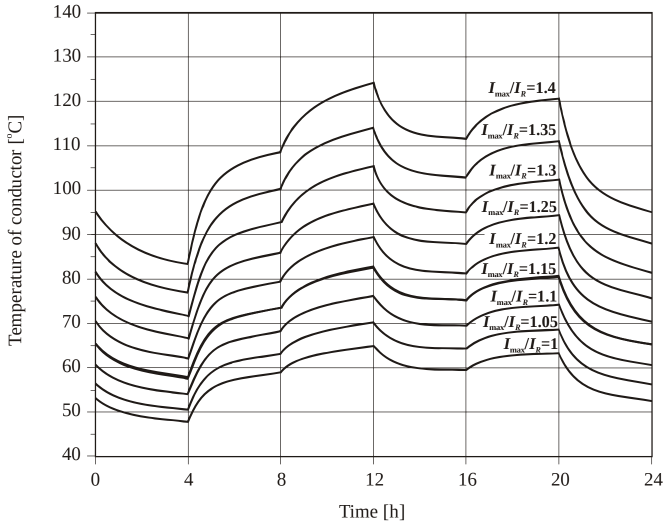

Fig. 2. Temperature variation during daily cyclic loading

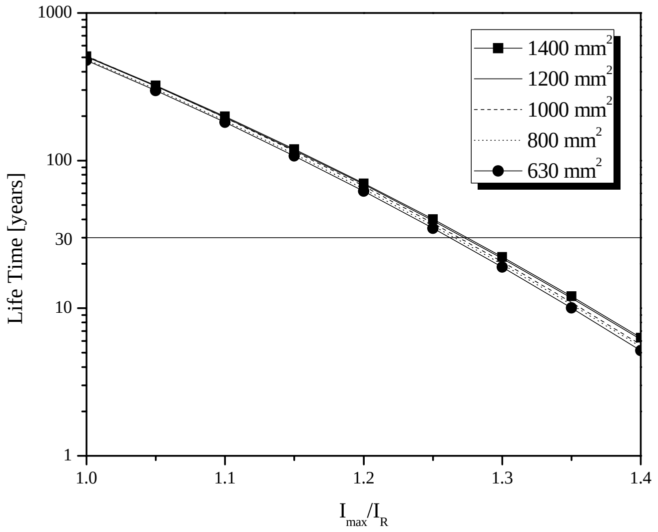

Fig. 3. Life time of cables for cycle loading

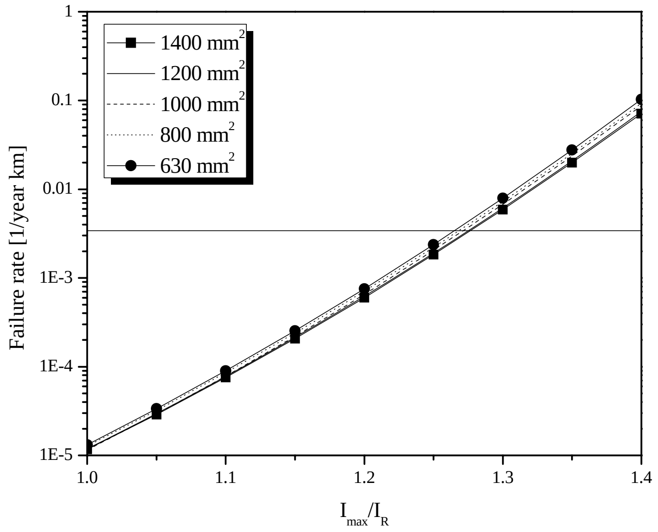

Fig. 4. Failure rate of cables at the end of design life

Fig. 3 shows expected life time of single-core XLPE cables with different cross-section areas in the case of daily cyclic loading as function of overload factor. Having in mind that design life of cable is 30 years, it is obvious that for daily cyclic diagram shown in Table III cables can be overloaded more than 27% without shortening the life time. As previously noticed, according to the Fig. 2, overload factor of the cable for given daily cycle diagram and maximal temperature at 90ºC is 1.2. Fig. 3 shows that cable life time from the aspect of electrothermal aging, for given overload factor of 1.2, is 65 years. For cyclic rating factor of 1.176 calculated according to relevant standard, life time from the aspect of electrothermal aging is approximately 100 years. Fig. 4 shows results of failure rate calculation at the end of design life time. As can be seen from this figure, for overload factor of 1.176 or 1.2, values of failure rates at the end of design life time are very low.

V. Conclusion

In this paper, a heating analysis of single-core XLPE cables buried in the ground, at daily load cycle, is conducted. For the assumed daily load cycle, cyclic rating factors and daily temperature variation at different values of overload factor are determined. On the basis of obtained results, it is shown that rated temperature is attained at value of overload factor slightly higher than cyclic rating factor value. Expected cable life time for different values of overload factor, respecting the daily cable temperature variation, is determined. On the basis of obtained results, it is concluded that overload capability of single-core XLPE cable is greater than one obtained by relevant IEC standard, when calculating with design life time.

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